

## Single top quark production at the Tevatron

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The production of single-top quarks occurs via the weak interaction at the Fermilab Tevatron proton-antiproton collider. Single top quark events are selected in the lepton+jets final state by CDF and D0 and in the missing transverse energy plus jets final state by CDF. Multivariate classifiers separate the  $s$ -channel and  $t$ -channel single-top signals from the large backgrounds. The combination of CDF and D0 results leads to the first observation of the  $s$ -channel mode of single top quark production. The  $t$ -channel and single top combined cross sections have also been measured.

### 1 Introduction

The top quark is central to understanding physics in the Standard Model (SM) and beyond. The study of single top quark production in particular provides unparalleled access to the weak interaction of the top quark<sup>1</sup>. This paper summarizes single-top quark measurements from the Tevatron proton-antiproton collider at Fermilab. The Tevatron operation ended in 2011, with CDF and D0 each collecting  $10 \text{ fb}^{-1}$  of proton-antiproton data<sup>2</sup> at a center-of-mass energy of 1.96 TeV.

Single top quark production proceeds via the  $t$ -channel exchange of a  $W$  boson between a heavy quark line and a light quark line, shown in Fig. 1(a), the  $s$ -channel production and decay of a virtual  $W$  boson, shown in Fig. 1(b), or the production of a top quark in association with a  $W$  boson. At the Tevatron, the  $t$ -channel cross section is largest, followed by the  $s$ -channel, while the associated production of a top quark and a  $W$  boson is too small to be observed.

The cross section at next-to-leading order in QCD with next-to-next-to-leading-log gluon resummation is  $2.10 \pm 0.13 \text{ pb}$  for the  $t$ -channel<sup>3</sup> and  $1.05 \pm 0.06 \text{ pb}$  for the  $s$ -channel<sup>4</sup>. These cross sections are calculated for a top quark mass of 172.5 GeV, the same mass used in the analyses reported here, which is close to the world average of  $173.2 \pm 0.9 \text{ GeV}$ <sup>5</sup>.

Single top quark production ( $t$ -channel and  $s$ -channel combined) was first observed by the CDF<sup>6</sup> and D0<sup>7</sup> collaborations at the Tevatron. The  $t$ -channel mode was also first isolated at the Tevatron, by the D0 collaboration<sup>8</sup>. The  $t$ -channel mode has a large cross section at the LHC, where it has also been observed by both ATLAS<sup>9</sup> and CMS<sup>10</sup>. The  $s$ -channel

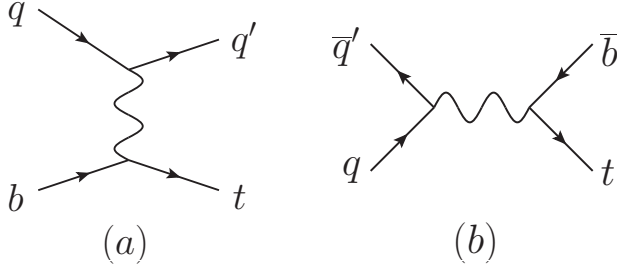


Figure 1 – Feynman diagrams for single top quark production in (a) the  $t$ -channel and (b) the  $s$ -channel.

production mode has a small cross section at the LHC due to the quark-antiquark initial state. To date only unpublished upper limits on  $s$ -channel production have been reported by the LHC collaborations.

## 2 Selection and modeling

### 2.1 Event selection

Top quarks decay essentially always to a  $W$  boson and a bottom quark. The final state is then selected based on the decay of the  $W$  boson. The lepton+jets final state has a large signal and manageable backgrounds. The event selection requires a high-transverse momentum isolated electron or muon, large missing transverse energy ( $\cancel{E}_T$ ), and two or three jets, at least one of which is required to be identified as originating from a  $b$ -quark ( $b$ -tag). Events with misreconstructed objects or phase space regions dominated by QCD multijet production are rejected. About  $10^5$  events are selected in data, with an expected signal contribution of about 400  $t$ -channel events and about 250  $s$ -channel events.

The CDF collaboration additionally includes the missing transverse energy ( $\cancel{E}_T$ ) plus jets final state, where the decay products of the  $W$  boson are not reconstructed or include a  $\tau$  lepton. This final state suffers from a large background due to multijet production, which is reduced effectively with a neural network (NN). About  $10^6$  events are selected in data per experiment, with an expected signal contribution of about 250  $s$ -channel events.

Events are separated into categories based on the  $b$ -tag information. Since  $t$ -channel production results in a light quark in addition to the top quark, these events mainly populate the single- $b$ -tag category. By contrast,  $s$ -channel events with two  $b$  quarks in the final state will mainly populate the two- $b$ -tag category. The CDF collaboration additionally separates events based on the  $b$ -tag likelihood.

### 2.2 Signal and background modeling

Simulation samples are used to model the single top signal and the dominant  $W$ +jets and top pair backgrounds, as well as smaller backgrounds from  $Z$ +jets and diboson production. Multijet events are modeled using data.

### 2.3 Systematic uncertainties

Sources of systematic uncertainty in the single-top measurements include the modeling of the signal, the modeling and normalization of the backgrounds, detector efficiencies and resolutions, jet energy scale and  $b$ -tag modeling. Both shape and normalization components are included. The total uncertainty on the background is between 15% and 20% depending on the analysis channel.

### 3 Single top production cross-section measurement

#### 3.1 CDF: combined single top

The combined  $t+s$  analysis with lepton+jets events at CDF with  $7.5 \text{ fb}^{-1}$  utilizes a NN discriminant that is trained with both  $t$ -channel and  $s$ -channel as the signal<sup>11</sup>. One of the main discriminating variables in the NN is the reconstructed mass of the top quark, which is shown for a zero-tag control region in Fig. 2(a). The NN distribution in the signal region is shown in Fig. 2(b).

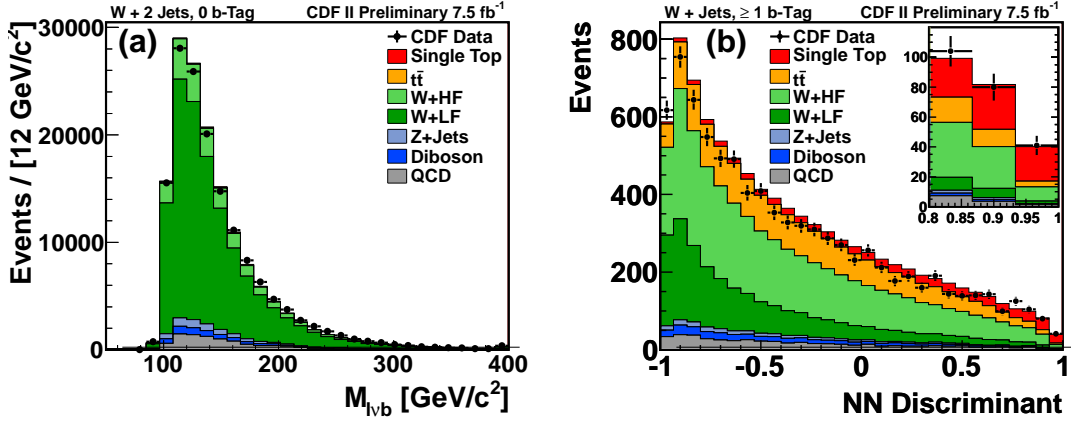


Figure 2 – CDF lepton+jets (a) reconstructed top quark mass for zero- $b$ -tag events and (b) NN discriminant for events with at least one  $b$ -tag.

The single top cross section measured in lepton+jets events is  $3.04^{+0.57}_{-0.53} \text{ pb}$ . The cross section measured in  $\cancel{E}_T$ +jets events is  $3.20^{+1.39}_{-1.43} \text{ pb}$ <sup>12</sup>. The lepton+jets measurement as a function of both  $s$ -channel and  $t$ -channel cross sections is shown in Fig. 4(a).

#### 3.2 D0: combined single top and $t$ -channel

The D0 single top analysis forms two multivariate discriminants, one optimized for the  $t$ -channel and one for the  $s$ -channel, shown in their respective signal regions in Fig. 3. These two discriminants are then combined into a single discriminant that is simultaneously sensitive to both  $t$ -channel and  $s$ -channel production.

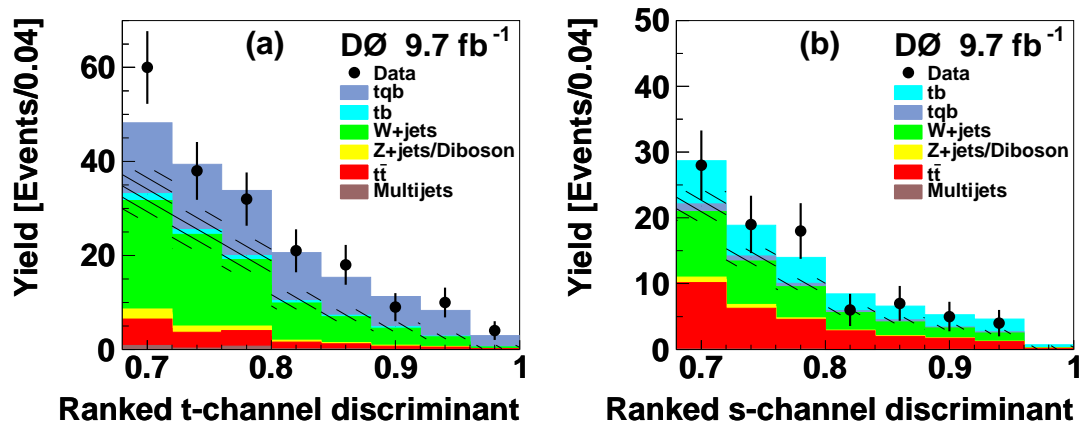


Figure 3 – D0 lepton+jets discriminant in the signal region (a) in the  $t$ -channel and (b) in the  $s$ -channel.

The resulting two-dimensional posterior density distribution is shown in Fig. 4(b), together with several models of new physics<sup>1,13,14</sup>. The cross-section measurements for the  $t$ -channel,

the  $s$ -channel and the combination are based on this distribution.

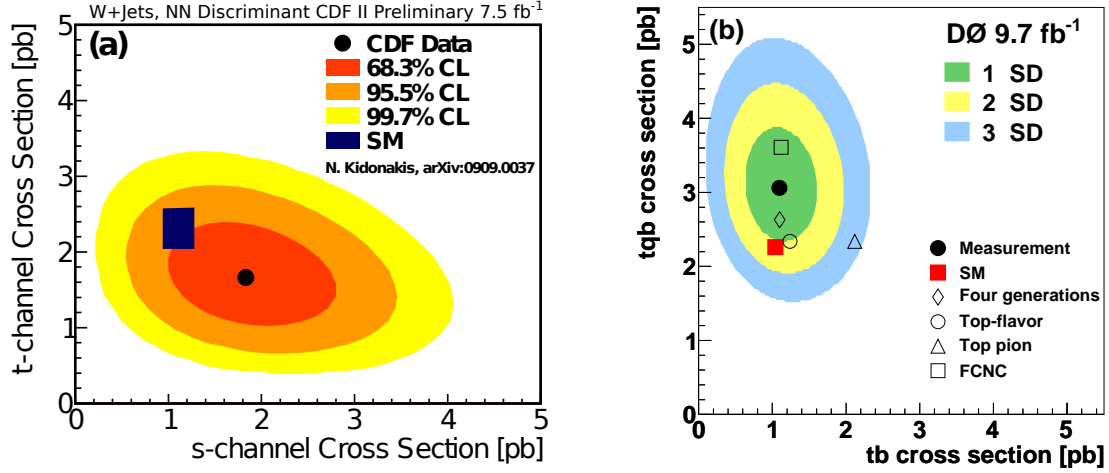


Figure 4 – Posterior density as a function of the  $t$ -channel and  $s$ -channel single top cross sections for (a) the CDF lepton+jets analysis and (b) the D0 analysis.

The  $t$ -channel cross section measured by D0 is  $3.07^{+0.53}_{-0.49}$  pb and the combined cross section is  $4.11^{+0.59}_{-0.55}$  pb.

### 3.3 CKM matrix element $V_{tb}$

Single top quark production proceeds via the  $tWb$  vertex, thus the production cross section is proportional to the square of the CKM matrix<sup>15,16</sup> element  $|V_{tb}|$ . The extraction of  $|V_{tb}|$  from the single top cross section measurement does not require assumptions about the number of quark generations or unitarity of the CKM matrix. The resulting 95% confidence level lower limit on  $|V_{tb}|$  from the CDF lepton+jets measurement is 0.78, the lower limit from the D0 measurement is 0.92, which is the most stringent limit from the Tevatron.

## 4 $s$ -channel observation

The two-dimensional D0 posterior density distribution in Fig. 4 is also used to extract a cross-section measurement for the  $s$ -channel. The measured cross section is  $1.10^{+0.26}_{-0.31}$  pb, and the observed significance is 3.7 standard deviations (SD).

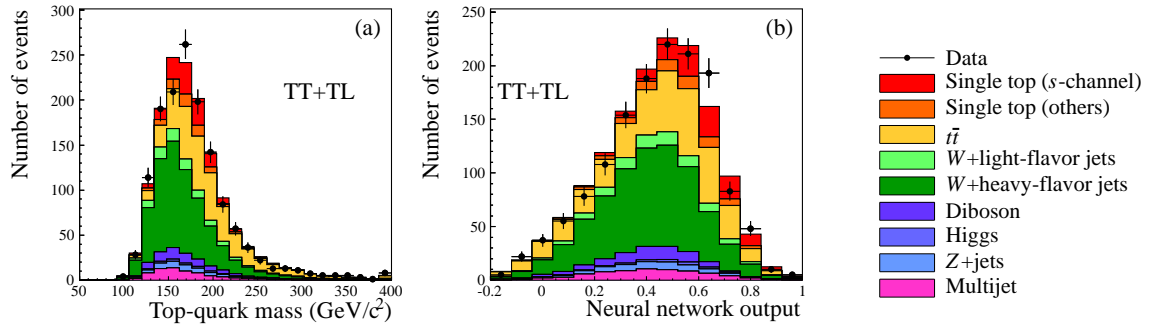


Figure 5 – CDF lepton+jets (a) reconstructed top quark mass and (b)  $s$ -channel discriminant in events with two  $b$ -tagged jets.

The CDF lepton+jets  $s$ -channel analysis forms a NN discriminant to separate the  $s$ -channel signal from the large backgrounds in several categories of events separated by the number loose

(L) and tight (T)  $b$ -tagged jets<sup>17</sup>. The discriminant distribution as well as the top quark mass are shown in Fig. 5.

The CDF lepton+jets analysis is combined with the  $\cancel{E}_T$ +jets analysis to obtain a cross section for  $s$ -channel single top quark production of  $1.36^{+0.37}_{-0.32}$  pb<sup>18</sup>. This corresponds to a significance of 4.2 SD.

The CDF lepton+jets and  $\cancel{E}_T$ +jets discriminants are combined with the D0 discriminant in the Tevatron combination<sup>19</sup>. The combined discriminant is shown in Fig. 6(a). This combination measures a cross section for  $s$ -channel production of  $1.29^{+0.26}_{-0.24}$  pb. The measurement has a significance of 6.3 SD, which makes this combination the first observation of single top production in the  $s$ -channel, and the first observation of a process through a Tevatron combination. A summary of all  $s$ -channel measurements is shown in Fig. 6(b).

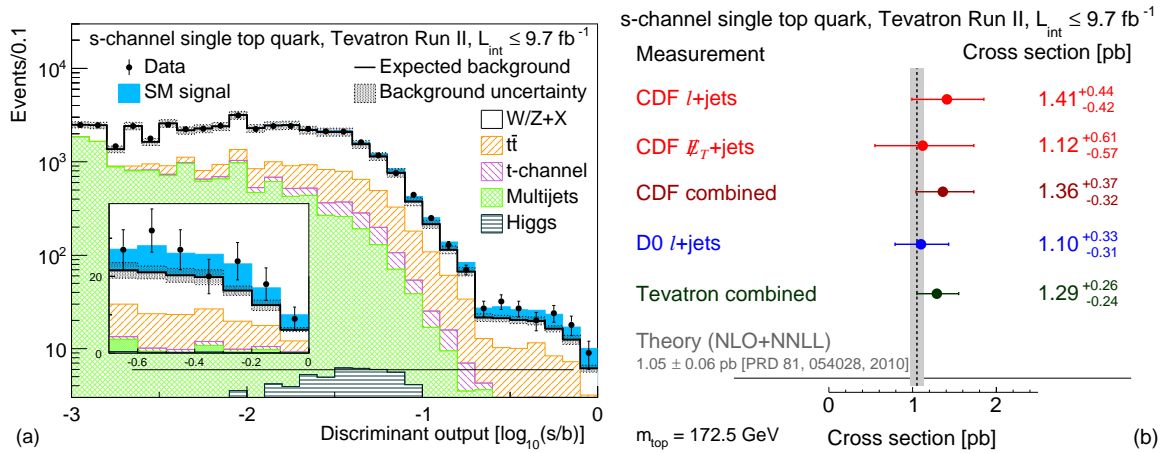


Figure 6 – Tevatron  $s$ -channel combination (a) sorted discriminant distribution and (b) summary of results.

## 5 Conclusions

The production of single top quarks was first observed at the Tevatron in 2009 independently by the CDF and D0 experiments. The cross section has been measured with an uncertainty of 14%. The two relevant production modes at the Tevatron have also been observed separately. The  $t$ -channel cross section has been measured with an uncertainty of 16%. The  $s$ -channel mode has recently been observed for the first time in a Tevatron combination of CDF and D0 with an uncertainty of 19% and a significance of 6.3 standard deviations.

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